ROOT AERATION IN RELATION TO PLANT GROWTH

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Matthew George Stahl

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ROOT AERATION IN RELATION TO PLANT GROWTH

I Introduction

Since the process of respiration in roots is identical with the respiration found to occur in other parts of the plant, it is of fundamental importance that the roots be assured of an adequate supply of oxygen and that undue accumulation of carbon dioxid be prevented.

In the seventeenth century Malphigi showed that germination of seeds could not take place in the absence of air. An enormous amount of quantitative data on the gaseous exchanges occurring in germinating seeds has since been accumulated.

The necessity for adequate root aeration in growing crops has long been emphasized in agricultural practice and has constituted one of the fundamental factors in the development of the present methods of tillage. Few experiments, however, have been reported which bear directly on the aeration of the soil by artificial means other than tillage. Day (7) grew barley, oats, wheat and peas in stone crocks which were artificially aerated by drawing air through them from below. After ten weeks' growth a slight advantage due to aeration was noted in the case of barley, wheat and oats. The peas in aerated pots showed considerable increase. Upon repeating the experiments the following year, the results with barley and wheat were contradictory and the effect of aeration on peas was not so marked. Soybeans and alfalfa showed increases due to aeration. At the Hatch Experiment Station, Stone (19) obtained increased growth of lettuce by drawing air through boxes for six hours daily.

The soil atmosphere has been shown by Russel and Appleyard (17) to contain less oxygen and considerably more carbon dioxid than the atmosphere above it. Its composition is largely determined by the biological processes

occurring within it. In addition to the free air of the soil, there is another atmosphere dissolved in the water and colloids of the soil. This consists mainly of carbon dioxid and nitrogen and has practically no oxygen. Leather (15) has shown that the soil air in the neighborhood of roots may contain abnormally high percentages of carbon dioxid. Surrounding the roots of Zea he found the air to contain from eight to sixteen percent of carbon dioxid and from 2.13 to thirteen percent of oxygen.

In a series of researches Livingston, Cannon, and Free (4) have studied the direct effects of growing plants in soils deficient in oxygen. The thirty species studied responded in different degrees to diminished partial pressure of oxygen. In general, a deficiency of oxygen existed when the oxygen comprised less than ten percent of the soil air with the remainder nitrogen. All species were able to maintain growth when the oxygen fell as low as two percent, provided that the amount of carbon dioxid was not excessive. Growth stopped and the roots were killed if they were entirely deprived of oxygen.

Since the extent of the free air of the soil bears an inverse ratio to the amount of water present, aeration is being recognized as a determining factor in the ecological distribution of plants.

The effects, direct and indirect, of poor aeration have received considerable attention in studying the problems of soil toxins and soil acidity. Clements (6) claims that lack of oxygen is the basic cause of these conditions.

Sudden and periodic submergence of roots and the consequent deleterious effect on growth, through interference with respiration and aeration, have called forth considerable research. Bergman (3) in greenhouse experiments has demonstrated that sudden flooding causes wilting and death in Vicia and Pelargonium but has no effect on Ranunculus and Cyperus. If artificial aeration be resorted to, the plants recover, form new roots and continue growth. He also found that when aeration is provided the development of plants is essen-

tially as good with swamp water as with nutrient solution. He attributed the slight difference observed to nutrition.

Hole and Singh (12) in experiments with seedlings of sal (Shorea robusta) found that poor soil aeration caused stunting of the roots and ultimately death through the accumulation of carbon dioxid and lack of oxygen.

Howard and Howard (14) have noted a marked aerotropism of the roots of indigo as the ground water rises in the soil. Deficient aeration causes the death of submerged roots and consequent wilting.

Wacker (20) found that the roots of Lupinus albus, Helianthus and Vicia did not grow as vigorously in water as in soil. In cultures of mud the roots of Vicia died off due to lack of oxygen and the accumulation of toxic decomposition products. Arker (2) in following up these studies found that the roots of these plants showed increased growth if air was bubbled through the culture solution. This he attributed to the greater mobility of the oxygen rather than an increased partial pressure.

Hall, Brenchley and Underwood (11) have attributed the superiority of cultures in solid media over water cultures entirely to the better aeration under the former conditions. By bubbling air continuously through water cultures of barley, he obtained an increase of sixty percent in dry weight over a period of eight weeks.

Stiles and Jorgensen (18) repeated the experiments with similar results. When Crone's solution was used with frequent renewal of cultures, the increase attributed to aeration amounted to sixty percent. When a modification of this solution without renewal was used, fifty-three percent increase was recorded. With Pfeffer's solution greater dry weight per plant was obtained and the aerated plants were heavier by twenty-four percent. Similar results were obtained with balsam. With buckwheat the difference obtained was not considered significant.

Free (9) grew buckwheat to maturity in Shive's solution. Sets of cultures through which oxygen, nitrogen and air were continuously bubbled yielded the same as untreated cultures. Sealing cultures appeared to exercise no effect. Cultures treated with carbon dioxid were killed within a few days. If carbon dioxid was displaced by air after the first day, partial recovery was noted.

Hole (13) has made the only attempt to follow quantitatively the relation of dissolved gases in fluid media. Seedlings of Sal were set up in solutions drawn from unaerated and aerated pots. Analysis showed the former to contain more carbon dioxid. After plants had grown in the solutions for three weeks, the dissolved oxygen and carbon dioxid were essentially the same in the two series. In further experiments Sal seedlings were grown in water cultures for eleven weeks. Aeration was accomplished by drawing air thru the cultures for five minutes three times daily. In both root and shoot development the non-aerated series were slightly superior. Analysis showed the gaseous content of the solutions in both series to be essentially the same at the end of the experimental period.

II Scope of Present Work

The work reported in this paper has been undertaken mainly to study the effects of varying degrees of aeration, to follow more closely the gaseous relations existing under water culture conditions with barley, corn and beans and to test the effect of increased and diminished partial pressures of oxygen and carbon dioxid on these plants.

III Apparatus and Methods

As the work progressed, constant modifications in technique were found necessary. In the experiments on aeration pint Mason jars, each holding 900cc of culture fluid, were used. These jars were washed in cleaning mixture, rinsed in distilled water and slowly dried in an oven before each experiment. The

corks used were of the usual type and were thoroughly coated with paraffin.

The hydrogen-ion concentration was determined by the colorimetric method of Clark and Lubs (5) as modified by Gillespie (10).

Oxygen determinations were made by the method of Winkler as outlined in "Standard Methods for the Examination of Water and Sewage" (1).

Samples were siphoned off into 250 cc. stoppered bottles and analysis made immediately after collection. The dissolved oxygen is reported in parts per million. In the case of Shive's solution the dissolved salts materially affected the results obtained. In as much as the results from the five bottles in each series were comparable, it was not deemed necessary to attempt correction.

The carbon dioxid is also reported in parts per million and was determined in tap and distilled water by the method outlined in the above publication (1). Samples of fifty or one hundred cubic centimetres were used where the carbon dioxid content was low. In handling solutions near saturation, only ten cubic centimetres were used.

The samples for gas analysis were all drawn from the center of the bottle by means of the siphon shown in Plate II (B). The diameter of the siphon and tube were sufficiently large to ensure rapid collection of the sample. Samples for hydrogen-ion determinations were collected in 25cc. stoppered test tubes.

The standard culture solution used was Shive's R_5C_2. This was made up as outlined in "A Plan for Cooperative Research on the Salt Requirements of Representative Agricultural Plants" (16). Tap water, distilled water and a modification of Crone's solution were also used at various times. Iron was added in the form of ferric chloride. This was rendered necessary because ferrous salts would interfere with the oxygen determinations. In long period cultures the solution was periodically tested for iron. The analysis of Crone's solution as used and of tap water are given in Table I. This Crone's solution was adopted

from Stiles (18) but only one-fourth the quantity of iron used by him was added. The water transpired was replaced daily after the loss became appreciable. For this purpose distilled water containing seven to nine parts per million of dissolved oxygen and an average of three parts per million of carbon dioxid was used.

The methods of germination of seeds and the technique of setting up the cultures are discussed later in cases where departures from the ordinary procedure seemed advisable.

The methods of securing aeration varied. Figure 1 shows a simple distribution apparatus constructed for use in minor experiments. The gas entered the cultures through capillary tubing having an inside bore of .6 mms.

In the first experiments with corn, the inlet tubes were made of glass tubing having a bore of .61 cm. and were drawn to a point. (See Fig. 2). For subsequent experiments the trap shown in Plate II (A) was devised. The capillary tube (a) conducts the gas to near the bottom of the vessel. The bubbles rise slowly between the inner and outer tube (b) and are permitted to escape near the surface of the culture solution through a small aperture (c). In this way slower and better aeration was secured and mechanical disturbance of the roots was greatly reduced.

For longer experiments involving periodic discontinuous aeration, the more elaborate apparatus shown in Plate I was devised and constructed by Dr. Hottes. Compressed air from the supply tap A passed into a reserve tank C through a gas washer D into the four distribution pipes F. Each distribution pipe had five outlet pipes G and an end cock M. Each outlet pipe was connected to the trap K of the culture vessel by glass tubing with rubber attachments H,H^1. The gas was washed and kept saturated by changing the distilled water in the washer D daily. By means of regulators E, which were connected to an electrically controlled contact clock, the supply of gas to any one of the

distribution tubes could be cut off at required periods.

The spring valve B provided for the regulation of the pressure which was never permitted to exceed five pounds. Further regulation of the rate of bubbling was attained by adjusting the release cock L or the end taps M. A uniform rate of sixty to eighty small bubbles per minute was thus ensured.

In the apparatus as photographed, the connecting pipe has been removed between N and O in order to provide for the increase of the partial pressure of oxygen from the cylinder P. The pressure of the oxygen is regulated in the bottle R, and then passes into the washer where it is mixed with air. By further adjustments CO_2 was also included in the circuit.

Since it was desirable to check the bubbling from time to time, the usual technique adopted to exclude light was unsuitable. The jars were therefore set in galvanized iron cans. (Plate I. T). By placing a quantity of sand in the cans, the height of the jar could be suitably adjusted. A suitable board covering fitting tightly round the neck of the jar served to exclude the light. (See Plate I. V). The cans were set on a table and were spaced and arranged so as to eliminate the possible effects of unequal illumination.

IV Experiments in Aeration

A. Corn

Experiment I

In November an experiment to determine the effects of aeration on corn grown in tap water was set up.

Funk Brother's selected disease free corn of the variety Ried's Yellow Dent was used. Uniform kernels were chosen and placed in moist sphagnum. When the plumules were 3 cm. long the seedlings were transferred from diffuse the sphagnum light to the culture vessels. Four series each containing five cultures were used, only one plant being used per jar. Figure 2 shows the method of setting up

the cultures in this experiment. The seedlings were attached by a rubber band (A) to a glass plate (B) with blunted edges. The corks were provided with holes for the plant, the inlet tube and the siphon.

The amount of dissolved oxygen and carbon dioxid was determined weekly, a sample for analysis being collected from each jar. The average result for each series is given in Table 2. A variation of as much as three parts per million occurred in individual cultures.

The plants were grown for a period of 28 days from sowing. After two weeks mold appeared on kernels of several cultures and had an evident effect on growth. The diseased plants were discarded. At the end of the period all plants were of poor color. The heights and green weights (Table 2) indicate a slight superiority in favor of the non-aerated cultures.

Experiment II

A similar experiment with improved method of aeration was set up in May when light and temperature conditions were more favorable. Only six cultures with surface sterilized seed were used. Three of these received continuous aeration. In the previous experiment, despite the precaution taken to protect the roots from mechanical disturbance by inserting a glass plate, they may have suffered through agitation. This factor was entirely absent in the second experiment. The seedlings were set up before the first leaf had emerged from the coleoptile and were subjected immediately to aeration.

From the 8th to the 20th day after setting up, each culture was analysed for dissolved oxygen. By thus changing 250cc. of the water daily and replacing it with tap water containing very little dissolved oxygen, a material difference in the amount of dissolved gas present was secured. The daily analysis for oxygen is given in Table 5, and the results in Table 3.

Experiment III

In the next experiment corn was grown in Shive's solution for 40 days from germination. In all 36 cultures were set up in series of six. The treatments being

S_1	Control
S_2	Sealed
S_3	Aerated 24 hours per week midway between culture renewals
S_4	Aerated 15 min. per diem, six days per week
S_5	Aerated 9 hrs. " " " " " "
S_6	Continuous aeration.

In order to obtain disease free cultures and prevent excessive diffusion the usual corks were not used. Ordinary "ball" Mason jar tops were provided with tubulatures as shown in Plate II (A). The smaller tubes (m,n) sufficed for the aeration trap and to add or remove solution. The joints were made air tight by close fitting rubber. When not in use the tube (n) was plugged with a length of capillary tubing. Before use the tops were thoroly waxed.

The seedlings were germinated in vials made from test tubes. These fitted into the larger tubulatures (o,p). The vials were cleaned and then set in sand containing 60% moisture. Surface sterile seeds were germinated between blotting paper and were planted in these vials when the radicles were 1 cm. long. They were then covered with sand and watered. They were sealed on the following day by inverting them in a mixture of paraffin and vaseline, after which they were reset in moist sand until shoots had appeared through the seal. The vials were then carefully removed from the sand and only those having healthy roots protruding were set in the tubulatures of the jar tops.

Two plants were set in each jar. After 15 days, however, one was removed from each jar, and replaced by a tight-fitting paraffined cork.

The culture solution was renewed four times during the experiment, on the 12th, 20th, 28th, 36th days. Analysis for dissolved oxygen and hydrogen-ion determinations were made on these days. The operations of setting up and

and harvesting were each spread over two days, half of the cultures in each series being attended to on each day.

The relative position of the series was changed from time to time during the experiment. The pertinent data are given in Table 4.

By taking measurements of the longest leaf and of the total leaf length, obtained by adding the measurements of each leaf from base to tip, the growth of each plant was followed. Using the longest leaf or the total leaf length as criteria of growth, the range of individuals from the various series overlap considerably. Their averages show little difference when plotted on paper. In dry weight there is no significant difference between the series.

B. Experiments with Beans

In these experiments the variety Extra Early Refugee, supplied by the Vaughan Seed Company, Chicago, was used.

Experiment I

In the first experiment seeds weighing 350 to 360 mgs. were selected. The seeds were set to germinate in moist clean sand in diffuse daylight. When the hypocotyls were 4 to 5 cms. long, ten seedlings were selected and set up in the usual manner. The cultures were left in diffuse daylight and the shoots kept moist by inverted jars until the first leaves were open and the epicotyls began to elongate. They were then attached to the apparatus and five were continuously aerated. The plants were grown to maturity in Shive's solution.

All the plants made healthy growth and no difference between the series was noticeable up to the time of flowering. Flowers appeared in both series at approximately the same time. Each plant bore from seven to nine flowers. The number of pods set per plant varied from one to four in the aerated seried. In the non-aerated series all the plants had two or three pods. The leaves which fell, as the plants reached maturity, were collected and preserved. The culture solution was renewed on the 16th, 24th, 29th, 38th days after germination. In

renewing the culture solution the cork and plant were lifted from the jar and quickly placed in the new jar, which had previously been filled with fresh solution.

Determinations of the hydrogen-ion concentration and of the dissolved oxygen were made from the solution removed on each of these days. The hydrogen-ion concentration had been changed an equal amount in both series and no differences could be attributed to the effects of aeration. The dissolved oxygen in the aerated series was generally higher by one to two parts per million.

The cultures were taken down when the pods began to dry and the leaves turned yellow. From the data on the green weight presented in Table 6 and the photographs on Plate 3, it can be seen that the plants in the aerated series matured slightly earlier than in the non-aerated series. The dry weight determinations show that both in the tops and roots the aerated plants were superior. There was little noticeable difference between the length of roots in the two series. This is in contrast with the results of the next experiment, in which the roots were not disturbed by renewal of the solution.

Experiment II

In this experiment twenty cultures were divided into two series of ten each. The first series received continuous aeration. The plants were grown up to the time of flowering. Half of the number in each series were harvested on May 1st, and the remainder on May 7th. The results appear in Table 7.

In this experiment the culture solution (Shive's R_5C_2) was not renewed. There appeared a distinct difference in the extent of the root development. This is clearly shown in Plates 4 and 5. In the dry weights the aerated series were superior. The dry weight of the roots particularly shows a remarkable increase which can be attributed to aeration.

Experiment III

In order to compare the growth of beans in Shive's solution and Crone's solution twenty-three cultures were used.

For this experiment the seeds were germinated in sphagnum until three days old. They were then transferred to paraffined cheesecloth stretched tightly over flowing tap water. After two days the water was replaced by Crone's solution diluted to one-fifth of its normal strength. On the seventh day the solution was replaced by full strength solution. After a further period of twenty-four hours the young plants were transferred to Mason jars and were set up in the usual manner. Twenty jars contained Crone's solution and the remaining three had Shive's solution. Iron was added to all the cultures on the tenth day and continuous aeration was started in ten of the jars containing Crone's solution.

The earlier growth of the tops was good in all the cultures. After the twenty-fifth day, however, the tender parts of the plants began to shrivel and die. The plants were therefore harvested on the 27th day, Only seven cultures in each series of Crone's solution were harvested.

From the beginning the roots in Crone's solution made very poor growth. They were stubby, profusely branched and of a slightly brownish color. There was little noticeable difference between the aerated and the control series in Crone's solution. In Shive's solution the root growth was similar to that observed in previous experiments. After the 25th day the plants in Crone's solution began to produce new roots.

Plate 6 shows the comparative root systems in the two solutions. The photograph was taken several days after the remaining plants were harvested. The jar in the center shows the extent of the secondary root development at that time, while the jar on the right shows the appearance of the roots in the average culture at the time of harvest.

The results of the experiment presented in Table 8 show distinctly the difference in the root development in Shive's and Crone's solutions. In dry weight the tops in Crone's solution were slightly better in the aerated series.

C. Experiments with Barley

Experiment I

For this experiment a selected strain of barley was obtained from the Plant Breeding Department of the University of Illinois. The seeds were germinated by the method described in "A Plan for Cooperative Research on the Salt Requirements of Representative Agricultural Plants" (16). The method of setting up the cultures is shown in Plate 2. Shive's R_5C_2 solution was used and was renewed once only.

Uniform seedlings from the germinator were washed in a shallow pan containing one-fifth normal nutrient solution. They were then lowered into the vials (Plate 2 C) until the kernels rested on the bottom of the vials, and the roots were freely suspended in the culture solution. They were then adjusted so that the kernels were just above the solution. The plants were held in place by cotton plugs. After the third leaf appeared the plugs were adjusted to permit titlers to develop freely. Two plants were grown in each pint jar. The plants made good growth in all the cultures. After the fourth week a few leaves became rusted and one plant in each series became infected with mold. The cultures containing them were therefore discarded.

The plants were measured and harvested on the 57th day after they were set out to germinate. At this time the amount of root growth appeared about the same in both series. The tops in the aerated series appeared more vigorous. In harvesting the plants the tops in each culture were taken separately. Since the roots of the two plants in each jar had intertwined, no attempt was made to separate them. The results appear in Table 9 and show that the aerated cultures had produced more leaves and a greater dry weight.

V. Effects of Increased and Decreased Partial Pressure of Oxygen on the Growth of Corn, Beans and Barley

The experiments reported in this section were undertaken in an attempt to follow more closely the relation existing between the concentration of dissolved oxygen and the rate of growth.

A. Corn

In these experiments seedlings with erect stems and straight roots were deemed necessary. To this end the use of the ragdoll was resorted to. Surface sterilized seedlings were placed in sterile ragdolls for three to five days. They were removed before sufficiently large to suffer root or shoot injury and were placed in diffuse light until chlorophyll had developed.

Experiment I

Uniform seedlings were selected when the coleoptyle was 2.5 cms. long and the roots from 7.5 to 8 cms. long. Two were then set up in each of a series of calcium chloride cylinders and were held in position by means of a cotton plug. A strip of filter paper, about two centimeters in breadth, was placed inside the vessel and served to draw up sufficient moisture for the developing seedlings. The portion of the cylinder below the construction was filled with water. The gas, which was supplied through the aperture near the base of the cylinder, was thus bubbled through water before coming in contact with the roots.

Of the five cylinders used, two were supplied with a slow current of oxygen from the small distribution apparatus, two were attached to the air supply and the remaining one served as a control.

In the first fifteen hours the roots in all vessels had increased from 2 to 2.5 cms. as measured on the outside of the vessel. After forty hours an increase of 8.2 cm. was noted in those attached to the oxygen apparatus. The roots had grown down through the constriction of the cylinder and had entered the water

where a slight curvature had taken place. In the first 8 cms. below the kernel small branch roots varying in length from .2 to .8 cm. had been produced. Below this was a region of 5 cm. bearing abundant root hairs. The end region of 3.2 cms. (2.8 of which was under water) was entirely free. In the cylinders attached to the air supply essentially the same behavior was noted and the roots had increased an average of 7.9 cms. After making an initial growth of 2.6 cms. the roots in the control vessel became injured through lack of moisture.

Experiments in which the portion of the cylinders above the constriction were filled with moist sphagnum gave the same results.

From these experiments it may be concluded that the roots of corn, when grown in an atmosphere which is moving continuously, do not show any increase in the amount of growth if the air is enriched with oxygen.

Experiment II

In the next experiment selected corn seedlings of the same size were set up in tall glass cylinders 26 cms. in height and having an internal diameter of 2.6 to 3 cms. Each vessel contained about 120 ccs. of distilled water. The seedlings were secured in the vessel by means of cotton plugs loosely wrapped around the coleoptyle and were adjusted so that the kernels were .5 cm. above the level of the water.

Ten cultures were set up. In five cultures the dissolved oxygen content was 6.2 to 8.4 parts per million, while in the remainder this had been increased to 34.2 p.p.M. by passing oxygen into a ten litre bottle containing four litres of water and shaking thoroughly. In order to maintain this difference in dissolved oxygen the plugs were sealed with vaseline and the water in all cultures was renewed at intervals of 20 to 24 hours. For analysis the contents of each series of cylinders was poured into a litre flask and 250 ccs. siphoned off and analyzed.

The results are summarized below and indicate no difference due to the

higher percentage of dissolved oxygen.

	Length in cms. June 12th 6 p.m. Root	Shoot	June 17th 6 p.m. Root	Shoot	Increase Root	Shoot	O2
Series 1	14.1	4.60	28.75	20.6	14.65	16.0	8.4
Series 2	13.8	4.54	28.52	20.25	14.72	15.72	21.6

At the time of taking the cultures down, the main roots had made considerable growth and had produced branch roots from 2 to 5 cms. in length. No class difference in the length of these branches was evident. The secondary roots had elongated from 15 to 20 cms. Throughout the period of growth the increments were noted from time to time by marks on the exterior of the cylinders. These showed that the amount of growth in periods ranging from 5 to 20 hours was uniform in both series. Measurements of the tops from the tip of the coleoptyle to the end of the longest leaf were made at intervals. The amount of increase was approximately the same in both series.

B. Experiments with Beans

Selected seeds were germinated in sphagnum until the radicle was 2.5 cms. long. They were then transferred to 250 cc. bottles with narrow necks and were secured in position by means of cotton plugs. After three days in a moist chamber in diffuse light, five bottles were attached to the small distribution apparatus as shown in Figure 1 (A). By bubbling oxygen through them the amount of this gas in solution was maintained between 14 and 33 p.p.M. After three weeks growth in Crone's solution there was no apparent difference due to treatment with oxygen. Dry weight determinations showed more individual variability within the series than class variation between the series.

Four seedlings which were injured by the removal of all secondary roots, when these had attained a length of 3 centimeters, showed more rapid root production when grown in water rich in oxygen.

C. Experiments with Barley

For these experiments grains of Hulless barley obtained from the Vaughan Seed Company, Chicago, were used. The seeds were carefully selected and sterilized by immersion for twenty minutes in chloramene T. They were then washed twice in distilled water and placed in a sterilized ragdoll. The ragdolls were set in a 15°C constant temperature case for four days until roots up to 2.5 cm. were developed. They were then transferred to cheesecloth over a pan of freshly boiled distilled water, at room temperature, and germination was permitted to continue until the roots were 6 cms. long and the coleoptyle 3.5 cms. long. Seedlings were then selected for uniformity and were set in a pan of distilled water from which they were transferred to the various culture vessels. Where nutrient solution was used the seedlings were placed in 1/10 normal solutions for a few hours prior to setting up. All cultures were placed in diffuse daylight for twenty-four hours at a temperature of 22 to 25°C. After which they were submitted to treatment.

Experiment I

Four seedlings were each measured and set in a 250 cc. Erlenmeyer flask containing tap water. In a series of five flasks the dissolved oxygen was maintained between 16 and 30 p.p.M. by renewing the solution every twenty-four hours. In the second series of five cultures the oxygen was kept below 2 p.p.M. by daily renewal with tap water containing .1 to .4 p.p.M. The seedlings were secured in position by means of cotton plugs wrapped around the coleoptyles and were placed so that the kernels were about half a centimeter above the level of the water. Renewal of the water was affected by lifting the plugs from the old flasks to new ones containing fresh water. Analysis for dissolved gases were made by compounding duplicate samples from each series of discarded flasks.

After six days each seedling was again measured. At the end of this

period a marked difference in the amount of growth in the tops was noticeable. From the table below it can readily be seen that, in the length of both the first and the second leaves, the cultures containing the higher amount of dissolved oxygen were superior.

It would thus appear that the seedlings in the lower series had an insufficient supply of oxygen even though this supply had been constantly renewed.

Culture	June 13th		June 19th			Dissolved O_2
	Root	Shoot	Root	Shoot		average
	cms.	cms.	cms.	1	2	ppm.
1	9.3	6.0	11.1	15.4	10.3	1.2
2	9.33	5.56	11.2	14.62	12.0	1.2
3	10.4	59	11.8	15.1	11.7	.9
4	10.4	5.4	12.5	13.3	15.1	.9
5	9.8	5.7	12.4	14.6	10.7	
6	10.3	5.2	11.45	16.9	13.2	21.0
7	10.2	6.1	12.2	17.85	15.2	21.0
8	9.7	5.4	11.6	16.2	15.3	19.7
9	10.1	5.8	12.2	17.2	15.4	19.7
10	9.3	5.2	13.6	15.1	14.2	

Experiment II

In order to test this further, ten cultures were set up in Crone's solution. Five seedlings were set in corks in the usual manner in pint Mason jars. The oxygen content in a series of five was kept high by renewal of the solution every forty-eight hours. The solution removed was shaken up with oxygen and replaced two days afterwards. The experiment was carried on over a period of three weeks. The cultures were kept at 15°C.

At the end of the period no difference was noticeable. Growth, however, had been very slow, owing to the comparatively low temperature.

Experiment III

In this experiment the effect of an increased partial pressure of oxygen was again studied. Eight cultures were set up in distilled water, eight in tap water, six in Shive's solution and six in Crone's solution.

As soon as the shoots were 6 cms. long, half the number of cultures in each series was attached to the distribution apparatus and were subjected to continuous aeration with air enriched with oxygen. Analyses for dissolved oxygen were made daily. Two control cultures in tap water were used for this purpose and a sample was collected from each on alternate days. In this way the oxygen content was kept at 16 to 20 p.p.M. in half of the cultures while the remainder had from 6 to 8.5 parts per million.

The plants made good growth in all solutions. After one week very distinct differences in the nature of the roots became apparent. The pictures (shown in Plates 7 - 10) were taken shortly after the root development became distinctive. These differences were much more marked when the cultures were taken down after thirteen days treatment. At that time the following notes were made:

"In distilled water (AP). Root development quite extensive, but not as much as in any other series. Root hair development pronounced at points of curvature. Laterals developed chiefly in lower half of roots and appear better in the aerated series (APA).

Tap water (T). Root growth characteristic. Main roots yellowish in color with well marked root hairs. Branches long and white in color. Branches slightly shorter in non-aerated series.

In Shive's solution (SH). Roots long, white with abundant characteristic long branches. Featherlike. Root hairs developed chiefly at points of curvature. No marked differences between aerated and non-aerated.

Crone's solution (Cr). On the whole the roots in this series are very much shorter than in others. Branching occurs chiefly along lower-most third of the roots in a comb like manner. Branches stubby and thicker than in all other series. Root hairs well developed".

It can thus be seen that in the four treatments the external

morphology of the root was distinctive and was determined by the respective nutrient medium. No difference could be attributed to the increased partial pressure of oxygen. The roots in Crone's solution developed characteristics analagous to those shown by beans in the same solution. In the tops there was little to choose between Crone's and Shive's solution. Tap water gave good growth, the leaves being slightly narrower and more harsh to the touch.

The plants were harvested after thirteen days treatment, or twenty days after placing in the ragdoll. The average height for each culture was determined by an exact measurement of each seedling. The weights were determined on an analytical scale and bear out the observation that the increased amount of dissolved oxygen had not stimulated the plants in any way. The results appear in Table 10.

VI. The Effects of Increased Partial Pressure of Carbon Dioxid on The Growth of Corn, Beans and Barley

A. Corn

In order to test the effect of high concentrations of carbon dioxid over short periods of time on the growth of corn, the following experiment was undertaken.

Experiment I

Five seedlings were set up in each of four pint Mason jars. The height of each seedling was measured shortly after the first leaf had emerged. The treatment accorded the various jars was as follows:

Numbers 1 and 2 were attached to the distribution apparatus. The tap water, in which they were grown, was rapidly brought up to saturation by bubbling carbon dioxid through them. After fifteen hours these cultures were disconnected and the water in Number 2 was changed.

On the second day Number 3 was saturated with carbon dioxid for three

hours. The carbon dioxid was then expelled. On the fifth day it was again treated with carbon dioxid for twenty-two hours and on the sixth day air was bubbled through it for two hours. The fourth bottle was used as a control and received no treatment. The heights of the plants in each bottle were measured after 17, 29, 43, 96 hours and then at every twenty-four hour period for a week.

The average height per culture at each period of measurement is presented in Table 11, together with the average increment in growth per culture. In figure 3 the results are plotted together with the treatment. When the cultures were set up the first leaf had just emerged from the coleoptyle. After twenty-three hours of treatment it was observed that the first leaf had unfolded and the second was appearing in all plants of cultures 4 and 2, while in culture 3 the development was not as far advanced. The roots of 1 and 3 had only increased half the amount noted in the control. The roots of culture 4 had produced branches while none had developed in Number 1. Numbers 2 and 3 were intermediate. Thirty-six hours later the roots in all the cultures had branches.

After an additional forty-eight hours there was little apparent difference between cultures 2, 3 and 4. The roots had lengthened considerably. In Number 1, the elongation of the main roots had apparently ceased, though branches continued to grow. The seminal roots had elongated considerably.

After one week all the plants, with the exception of one in culture 1, had produced three leaves.

An analysis of the data seems to indicate that the initial treatment for seventeen hours had a slight depressing effect in culture 2, but that this was overcome after four days. The initial treatment for twenty-nine hours in culture 1 had a slight depressing effect - almost identical with that observed in the second culture. Since, however, it was subject to carbon dioxid (with falling concentration) for an additional period of hours, the effect was more permanent and could be plainly read in the developing plants.

In number 3 the initial rate of growth was almost identical with that in the control. Treatment for four hours caused a slight retardation. A second treatment for thirty-six hours caused a sudden drop in the growth rate.

In the case of the roots, the effect of the carbon dioxid can be seen in an initial suppression of branch roots and a retardation of the rate of elongation. The injured roots function and produce branches after a short time. The main burden of absorption, however, appears to be thrown on to the seminal roots which develop rapidly.

Experiment II

The effects of lower concentrations of carbon dioxid on corn were studied in the following manner.

Eleven corn seedlings were set up in tap water as described in Experiment II of the previous section. The vessels were divided into three series when the first leaf had emerged from the coleoptyle and was about 1 cm. long. The first two series of four seedlings each were attached to the distribution apparatus. A mixture of gases was then slowly bubbled through the vessels so that the amount of dissolved carbon dioxid was maintained in the neighborhood of 150 p.p.M. in the first series and 75 to 100 p.p.M. in the second series. The third series was used as a control and received no treatment.

The height of the seedling from the top of the coleoptyle to the tip of the leaf was measured daily over a period of one week. The average height of each series together with the daily increments in growth and the carbon dioxid treatment are given in Table 12. Some days after treatment was suspended some of the kernels showed signs of disease and it is not known what effect this has had on growth. In the amount of root development there was little difference noticeable in the cultures.

It may be concluded that corn grown in tap water containing carbon dioxid in amounts up to 15% saturation ~~does~~ not exhibit ~~any~~ no immediate signs of

toxicity. The conclusion is further substantiated by the measurements made thirteen days (316 hours) after the cultures were set up. The length of the tallest leaf, the length of the main root and the average length of the seminal roots are given in the table. The variations found are probably individual and hence cannot be correlated with the increased partial pressure of carbon dioxid.

B. Experiments with Beans

Eight bean plants which had grown in Crone's solution up to the time of flowering were used to test the effect of carbon dioxid on this plant. Six of these were divided into two series of three each. Prior to treatment these series had an average transpiration rate of 31 ccs. and 29 ccs. per plant per day. One series was saturated with carbon dioxid for a period of three hours. At the end of this period the plants showed signs of wilting and they were therefore disconnected. By the following morning they had recovered and could not be distinguished from the control series. After a period of twenty-four hours they were again treated with carbon dioxid for twenty-four hours. On the following day all the carbon dioxid was expelled by aeration.

In the treated series the transpiration rate had dropped nearly fifty percent after the third day of treatment. The individual plants did not respond to the same degree. After four days the leaves began to yellow and after one week two of the plants had been killed, the remaining one lost most of the leaves but produced new roots and continued to live. Another plant which had been treated for four hours only had lost all its older leaves but recovered sufficiently to start new roots and produce new leaves.

The toxic effect of carbon dioxid on fully developed bean plants is very marked.

C. Experiments with Barley

In order to test the effect of carbon dioxid on the growth of barley, duplicate cultures were set up in distilled water, tap water, Shive's solution,

Crone's solution and Crone's solution without iron. The cultures were set up when the coleoptyles were 4 to 4.5 cm. long and the roots 6.5 cm. long. After a day in diffuse light the heights from the corks were measured. One culture in each of the solutions was then attached to the distribution apparatus and a mixture of air containing 150 p.p.M. of carbon dioxid was passed through them for a period of twenty-four hours, after which they were treated with carbon dioxid alone for a period of eighteen hours. Some of the carbon dioxid was then lost by diffusion during a further period of twenty-four hours, after which it was rapidly expelled by passing air through the cultures. After twenty-four hours aeration, the cultures were left to stand. Measurements of the seedlings were made at periods of 18, 36, 54, 74 hours after treatment was started and at intervals of twenty-four hours thereafter until the seventh day. The height of each seedling and leaf was measured to the nearest millimeter; six measurements were made on each jar. By measuring a known seedling twice, a check on the accuracy of the measurements was maintained. These show that the effect of the carbon dioxid is noticeable within twenty-four hours, though growth continued in all cultures. The extent of the injury, however, was not sufficient to outweigh the differences due to nutrition in the various solutions.

The second leaves in all the treated cultures appeared later than in the corresponding control cultures. One week after treatment commenced, little difference was noticeable in the tops of the cultures in the nutrient solutions, though the treated cultures were in every case slightly shorter.

In the control cultures the various solutions again called forth the characteristic growth habits of the roots which had been noted in a previous experiment.

In the treated cultures branches were observed in Shive's solution and tap water. These, however, were shorter than in the corresponding control culture. In the Crone's solution no branches were observed at this time. The development of

root hairs however was extensive. In distilled water the roots were longer in the control cultures. On the fourteenth day after setting up the root characteristics were more pronounced. Branches had grown rapidly in the treated cultures of Shive's solution and tap water. The roots in treated cultures of Crone's solution had produced numerous branches above the level of the water.

After twenty days the tops in distilled water were dying and showed little difference. In Shive's solution and tap water the root development in the treated and control cultures was very similar. In Crone's solution very few branches had appeared in the treated culture. On this day the cultures were finally measured and harvested with the results appearing in Table 13. This table shows that in all series the control cultures had made more growth. The carbon dioxid has not affected the plants in the various media to the same degree.

VII. Experiments in Sand Cultures

The striking increased growth of the roots of beans in aerated cultures of Shive's solution suggested an inquiry into their response to increased oxygen supply in solid media.

Ten tall glass cylinders were filled with clean sterile sand which had been mixed with sufficient Shive's solution to bring the moisture content up to sixty percent saturation. Beans which had been germinated in sphagnum until the radicles were 2.5 cm. long were then planted - one in each cylinder. These were then set in diffuse daylight in a moist atmosphere until the hypocotyl had elongated and the first leaves began to unfold. Four of the cylinders were then attached to the small distribution apparatus. Oxygen was passed to the bottom of the vessels through long glass tubes for a period of ten minutes daily. On the eighth and fourteenth days the oxygen was run continuously for twelve hours. Two of the remaining cultures were attached to the air supply for a period of twelve hours on the eighth and fourteenth days. The remaining cultures received no

treatment.

The surface evaporation and the water lost by transpiration was replaced on alternate days in the first week and daily thereafter. Half of the water was added at the surface of the sand and the remainder down the aeration tube. Since the seedlings were chosen when very young the desired uniformity was not obtainable. Biweekly measurements of the leaf length and leaf breadth revealed no superiority which could be attributed to treatment. After eighteen days the plants were taken down. The roots were washed free of sand, replaced in their respective vessels and photographed forty-eight hours after (Plate XI). In all the cylinders treated with oxygen, the roots were longer than in the controls. The controls which had been treated with air weekly were intermediate in development. The plants were left in tap water. All the old leaves wilted and the roots died. After a week the plants had all produced new roots and leaves.

The results indicate that better development of the root system is attained by aeration and oxygenation. In order to increase the efficiency of the aeration, long narrow vessels were chosen. The aerating gases thus passed through a long narrow column of sand. This at the same time involves greater difficulty in securing adequate and equal distribution of the moisture. An attempt to overcome this was made by adding equal quantities above and below. There remains a possibility that uniform moisture distribution was not attained in the control cultures and that the shortness of the roots was due, in part at least, to this consideration.

VIII.

SUMMARY

In the experiments on aeration the three crops studied did not all respond to the same degree. While the growth of corn in tap water was comparatively poor, the results indicate that no increased growth in either root or shoot is obtained by continuous aeration or aeration for short periods at intervals. The concentration of dissolved oxygen showed no correlation with growth within the limits attained by aeration.

In Shive's solution aeration for varying periods over thirty-five days failed to produce any differentiation in either roots or tops. The character of the roots of corn manifested no modifications which could be attributed to aeration. If the elongation of the root is interferred with by contact with the sides of the vessel, root hairs develop occasionally at points a short distance behind the tip of the roots.

In the case of beans, aeration has had decided effects in increasing the dry weight of both tops and roots. Beans grown to maturity in Shive's solution, with frequent renewals, showed an increase of 19% in the dry weight of the tops. The roots alone increased by 33%. Up to flowering time plants grown in Shive's solution without renewal showed an increase amounting to 20%, while that of the roots was 60%. Plants grown a week longer showed 30% and 80% respectively. In Crone's solution, where the root system was profoundly modified, the tops increased by 16% and the roots decreased by 6%. Although individual variations were considerable, they are overshadowed by the effects of the treatment. The character of the roots in treated and control cultures was the same for a constant solution. The root development in Crone's solution was exceedingly poor.

In the case of barley, aeration in Shive's solution has produced an increase of 19% in the total dry weight, and 14% in the roots alone. Aeration

did not appear to affect the character of the roots or the production of root hairs.

When the partial pressure of the dissolved oxygen is increased above that of saturation at normal temperatures, no increased growth has been noted in corn, beans or barley. This appears to be true whether the higher pressure be obtained by frequent renewals of the solution or by bubbling oxygen through it. With barley grown in tap water, the results obtained indicate that, while there is sufficient oxygen in water containing six parts per million of oxygen, the process of growth is hindered when this pressure falls as low as .25 p.p.M.

Carbon dioxid has proved toxic to corn, beans and barley in high concentrations over short periods of time. Concentrations up to fifteen percent saturation have not been found to affect the development of corn seedlings adversely. The after effects of this gas are noticeable in all cases. The rate of acceleration of growth after treatment is dependent on the length of the time of treatment. If this be short, the recovery is rapid until the normal rate is regained.

In all the cases considered the roots were profoundly affected. The degree varied from entire suppression of branches and elongation to only a slight retardation of the rate of growth. In the case of barley the nature of the solution appeared to affect the rate and manner of recovery, In all the cases in which seedlings were used the roots continued to function and maintained the transpiration current.

In these experiments the lack of oxygen may have been a contributory cause.

The hydrogen-ion concentration has not been found to be materially affected by aeration.

CONCLUSIONS

In the experiments reported aeration has not produced increased growth in corn. The growth of this plant is not retarded or stimulated by aeration or oxygenation. This plant appears indifferent to any increase of the dissolved oxygen above six parts per million.

Aeration and oxygenation do not modify the character or the amount of root growth. In saturated solutions carbon dioxid exercises a toxic effect on seedlings of corn. Solutions containing up to fifteen percent of this gas produced no effect within one week.

Beans respond to aeration. The amount of increase in dry weight varies with the length of the growth period. The roots show a greater percentage increase than the entire plant. The nature of the solution in which the plants are grown affects the degree of response to aeration. No increased growth is produced in young plants if the partial pressure of the oxygen be increased above saturation under normal atmospheric conditions. In saturated solutions carbon dioxid is very toxic to well developed bean plants.

Barley responds to aeration. The character of the roots is not modified by aeration. The development of seedlings is retarded in solutions containing less than two parts per million of dissolved oxygen. Seedlings are impartial to any increase of the dissolved oxygen above saturation under normal atmospheric conditions. The composition of the nutrient solution determines the character of the root growth. Aeration has not been found to affect it.

If the nutrient solution be saturated with carbon dioxid for short periods growth is retarded and the roots become modified. The nature of the nutrient medium affects the rate of recovery after treatment.

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Table 1.

A.

Tap Water
From analysis of Illinois Water Survey
April 27th, 1920. No. 42806

Salts	p.p.m.
$NaNO_3$	1.70
Na_2SO_4	1.09
Na_2CO_3	66.14
$(NH_4)_2CO_3$	7.68
$MgCO_3$	95.96
$CaCO_3$	159.90
Fe_2O_3	3.49
Al_2O_3	3.19
SiO_2	22.10
Silicious bases	280.
Total	363.87 parts per million

B.

Crone's solution (Modified)

KNO_3	1.00	
$MgSO_4$	.25	
$CaSO_4$	.25	
K_2HPO_4	.25	
$FeCe_3$	.04	(Stiles used .10)

Distilled water 1000.0cc (Stiles used tap)

Table 2.

Results of Aeration of Corn Grown in Tap Water

(Period 28 days from sowing)

Treatment	Average height inches	Green weight Tops	Dissolved O_2
Not aerated	23.2	3.28	5.9
Aerated 10 minutes on alternate days	24.1	3.32	6.8
Aerated 1 hour daily	22.8	3.27	7.3
Aerated 12 hours daily	23.8	3.17	7.4
Continuous aeration	21.7	3.22	7.6

Table 3.

Effects of Aeration on Corn Grown in Tap Water

(Period of growth 22 days)

No.	Number Leaves	Height Inches	Length Roots		Green Weight		Dry Weight		
			Greatest	Average	Tops	Roots	Tops	Roots	Total
A1	5	18	16	9	2.59	1.11	.280	.0700	.350
A2	5	19.3	26	13	2.65	1.31	.313	.0955	.408
A3	5	20.1	15	12	2.58	1.27	.286	.0870	.373
Mean									.377
N1	5	17.8	14	11	2.89	1.29	.258	.0920	.350
N2	5	20.4	15	12	2.89	1.26	.282	.0865	.368
N3	5	19.1	16	12	2.43	1.20	.291	.0805	.371
Mean									.363

Table 4.

Effects of Aeration on Corn Grown in Shive's Solution
(Period of Growth 40 days)

Solution changed on 12th, 20th, 28th, 36th days

No.	Number Leaves	Number Leaves	Height Inches	Total Leaf Length	Green Weight Tops	Green Weight Roots	Dry Weight Tops	Dry Weight Roots	Total
S1	5	8.2	25.8	147.5	13.6	4.5	1.284	.198	1.482
S2	4	8.2	25.2	136.5	11.9	3.8	1.262	.192	1.354
S3	4	8	25.7	142.3	13.8	3.9	1.311	.186	1.497
S4	5	8.2	26	148.0	14.1	4.1	1.364	.201	1.565
S5	6	8.2	25.2	133.2	12.2	4.0	1.271	.197	1.468
S6	5	8	24.5	141.0	12.4	3.9	1.232	.191	1.423

Table 5.

Daily Analysis for Dissolved Oxygen of Six Cultures of Corn in Tap Water
(Oxygen in parts per million)

Treatment	Days after setting up											
	8	9	10	11	12	13	15	16	17	18	19	20
Aerated												
A1	8.2	6.0	6.9	6.2	5.8	5.2	7.9	6.9	7.9	6.9	6.4	5.8
A2	8.7	6.2	6.3	5.8	4.9	5.1	7.7	6.8	8.4	7.2	6.1	6.3
A3	8.2	6.7	6.1	5.7	4.3	5.7	7.7	6.7	7.6	7.2	6.2	5.4
Ave.	8.3	6.3	6.4	5.9	5.0	5.3	7.8	6.8	8.0	7.1	6.2	5.8
Not aerated												
N1	5.2	4.6	2.9	2.1	1.3	.8	4.3	2.3	1.6	.7	.6	.4
N2	7.9	4.8	2.8	2.1	.9	.7	3.6	1.8	1.8	.8	1.2	.3
N3	6.1	4.9	3.1	2.4	1.2	.9	3.7	2.1	1.9	1.1	.7	.5
Ave.	6.4	4.7	2.9	2.2	1.3	.8	3.9	2.1	1.7	.8	0.8	.4
Water added	.6	.25	.3	.6	.3		.3	1.3	.2	.2	.3	

Carbon dioxide	
Aerated	.5
Not aerated	3.2

Table 6.

Effects of Continuous Aeration on Beans Grown to Maturity in Shive's Solution

Solution Renewed on 16th, 24th, 29th, 38th days

Period of Growth February 1 - April 8

Treatment	Number	Green Weight Tops	Roots	Dry Weight Tops	Roots	Total	Seeds
Aerated	1	14.7	2.5	3.482	.218	3.70	1.63
	2	23.08	3.8	3.260	.216	3.836	2.31
	3	15.92	2.52	3.312	.193	3.505	1.64
	4	11.75	2.04	3.281	.211	3.492	1.41
	5	14.98	3.52	3.124	.184	3.408	.70
	Ave.					3.588	
Not aerated	1	17.8	1.46	2.971	.169	3.040	1.684
	2	20.72	1.65	3.174	.174	3.348	1.773
	3	19.45	1.70	2.212	.201	2.413	1.168
	4	23.6	2.24	3.023	.193	3.216	1.640
	5	15.18	2.21	2.871	.187	3.058	1.21
	Ave					3.015	

Table 7.

Effects of Aeration on Beans Grown in Shive's Solution

Growth Period March 29 - May 1, May 7

Solution not Changed

A. Harvested May 1.

Treatment	Number	Length Roots Number Leaves	Greatest	Average	Dry Weight Tops	Roots	Total
Aerated	1	9	15	11.5	1.304	.172	1.476
	2	10	14.5	10	1.262	.159	1.421
	3	8	16.3	11	.912	.194	1.106
	4	9	17	13.5	1.275	.177	1.452
	5	9	15	12	1.155	.172	1.327
Ave.							1.356
Not aerated	11	8	7	5.5	.804	.100	.904
	12	9	8.5	6.0	1.240	.1062	1.346
	13	8	10.5	6.0	1.033	.1152	1.148
	14	9	9.5	7.5	1.136	.1062	1.342
	15	9	9	7.5	.844	.119	.963
Ave.							1.121

B. Harvested May 7.

Aerated	6	18	14	1.142	.219	1.361
	7	13	11	1.637	.247	1.984
	8	15.5	13	1.788	.198	1.986
	9	15	12.5	1.779	.230	2.009
	10	15	13	1.788	.238	2.026
Ave.						1.877
Not aerated	16	6	5.5	1.344	.141	1.485
	17	7	5.5	1.120	.112	1.232
	18	8	5	1.370	.129	1.499
	19	8	6	1.210	.121	1.432
	20	8	4	1.440	.140	1.580
Ave.						1.446

Table 8.

Effects of Aeration on Beans Grown in Modified Crone's Solution

Solution Not Changed

Period of Growth May 10 - June 6th

Treatment	Number	Length Roots	Green Weight Tops	Green Weight Roots	Dry Weight Tops	Dry Weight Roots	Total
Aerated	1	2.25	9.2	.95	.860	.068	.928
	2	3	8.57	.85	.841	.072	.913
	3	2.25	9.83	.82	1.036	.067	1.103
	4	2.75	10.60	1.01	1.056	.084	1.140
	5	3	10.74	1.18	1.112	.092	1.214
	6	3.25	9.73	1.06	1.058	.082	1.142
	7	3	10.35	.93	1.187	.069	1.256
Ave.							1.099
Not aerated	1	2.75	10.17	1.01	1.090	.082	1.172
	2	3.50	8.95	.76	.850	.074	.924
	3	3.25	9.30	1.04	.811	.084	.895
	4	3.50	8.72	.83	.682	.063	.745
	5	3.25	10.11	1.24	1.022	.092	1.114
	6	3.50	8.95	.84	.792	.083	.873
	7	3.50	9.10	.92	.824	.083	.907
Ave.							.946
Shives	1	9.25	14.0	1.34	1.670	.143	1.813
R_5C_2	2	10.5	12.6	1.21	1.590	.137	1.727
Control Not aerated Ave.	3	Not harvested					1.770

Table 9.

Effects of Aeration on Barley Grown in Shive's Solution

Period of Growth April 3 - May 29

Solution Changed once only on May 7

Treatment	Number	Height Inches	Number Leaves	Dry Weight Tops	Roots	Total per jar
Aerated	1 A	23.0	17	.834		
	B	24.5	24	.942	.282	2.058
	2 A	20.2	17	.837		
	B	24.1	19	.882	.231	1.950
	3 A	26.1	20	.861		
	B	27.1	18	.841	.203	1.905
	4 A					
	B	(diseased)				
	5 A	19.4	23	.916		
	B	24.0	14	.672	.246	1.834
	6 A	24.2	18	.791		
	B	20.1	21	.842	.291	1.924
Mean				Average per plant		.9671
Not aerated	1 A	21.2	19	.792		
	B	18.6	16	.463	.227	1.482
	2 A					
	B	(diseased)				
	3 A	19.2	16	.743		
	B	19.4	17	.771	.215	1.729
	4 A	23.1	18	.821		
	B	19.2	15	.621	.244	1.686
	5 A	24.2	19	.864		
	B	21.3	14	.681	.221	1.766
	6 A	23.5	15	.514		
	B	22.2	16	.726	.191	1.431
Mean				Average per plant		.8094

Table 10

The Effect of Increased Partial Pressure of Oxygen on Growth of Barley in Distilled Water, Tap Water, Shive's Solution and Crone's Solution

Period of Aeration June 20 - July 3

Culture	Length Roots Greatest	Length Roots Average	No. Leaves	Height Tops(cms)	Green Weight tops	Dr. Wt. (mgs) Tops	Dr. Wt. (mgs) Roots	Dr. Wt. (mgs) Total	O2
APA1	29	26	2.2	14.70	.95	97	34	131	
APA2	29	25		15.94	.91	92	30	122	
APA3	27	25		15.64	.87	96	35	131	
APA4	28	24		14.87	.91	92	32	124	
Ave.	28	25		15.79	.86	94	33	127	17.2
APN1	24	22	2.2	16.50	.86	92	37	129	
APN2	26	24		14.90	.91	106	37	143	
APN3	17	16		15.60	.93	94	33	127	
APN4	22	20		15.20	.82	97	41	128	
Ave.	22	21		15.05	.88	97	37	132	6.8
TA1	19	19	3.0	18.64	1.22	118	42	160	
TA2	23	21		22.06	1.13	114	46	160	
TA3	21	19		22.02	1.26	129	71	200	
TA4	19	18		24.66	1.30	132	62	192	
Ave.	20	19		26.85	1.22	123	55	178	17.2
TN1	21	20	3.0	21.00	1.36	139	48	187	
TN2	26	22		20.20	1.26	137	37	174	
TN3	32	21		23.20	1.26	138	36	174	
TN4	25	22		23.10	1.23	131	58	189	
Ave.	26	21		21.87	1.27	136	45	179	6.8
CrA1	14	13	3.0	25.20	2.30	176	40	216	
CrA2	15	14		27.80	1.96	145	42	187	
CrA3	16	15		26.90	1.94	159	39	198	
Ave.	15	14		26.67	2.07	160	40	200	17.2
CrN1	16	14	3.0	26.50	2.26	178	45	223	
CrN2	15	14		25.20	2.14	160	40	200	
CrN3	16	14		24.60	2.05	145	39	184	
Ave.	16	14		25.43	2.15	161	41	202	6.8
ShA1	23	23	3.0	26.80	2.13	170	35	185	
ShA2	31	22		25.70	2.10	164	42	206	
ShA3	27	19		26.90	1.98	153	39	192	
Ave.	27	21		26.47	2.07	162	39	194	11.4
ShN1	28	17	3.0	27.30	1.99	162	38	200	
ShN2	23	21		26.20	2.02	173	36	209	
ShN3	22	20		23.70	1.88	157	35	192	
Ave.	24	19		26.40	1.96	164	36	200	2.1

Table No. 11.

Effects of Saturation with CO_2 For Short Periods, on Growth of Corn in Tap Water

(Height measured in centimeters)

Time in Hours	0	17	29	43	96	120	144	168	192	264
No. 1	4.82	5.42	6.24	7.58	12.20	15.8	18.8	20.4	22.45	30.08
No. 2	4.85	5.40	6.70	8.50	15.14	19.99	22.5	24.5	26.8	35.0
No. 3	4.12	5.10	6.32	7.60	13.30	17.1	18.7	19.2	20.8	26.2
No. 4	4.96	6.02	7.60	9.46	16.30	20.1	22.6	24.7	28.0	33.5

Increments

No. 1	.6	.82	1.34	4.6	3.5	3.	1.6	2.0	7.6
No. 2	.5	1.30	1.8	6.6	4.8	2.5	2.0	2.3	8.2
No. 3	.98	1.2	1.3	5.7	3.8	1.6	.5	1.6	5.4
No. 4	1.1	1.6	1.9	6.84	3.8	3.8	2.1	3.3	5.5

Table No. 12.

Effect of Low Concentration of CO_2 on Growth of Corn Seedlings in Tap Water

Time in Hours	0	20	48	72	96	110	134	Tops	312 Main Roots	Seminal Roots
	Ht. in cms.									
Series 1	2.6	5.8	11.3	14.3	17.7	19.9	21.7	32.5	38	28
2	2.7	5.0	11.9	15.0	17.0	19.7	22.5	34.5	33	27
3	2.9	5.4	11.5	15.4	18.3	20.9	23.4	34	40	27
Increase										
Series 1	3.2	5.5	3.0	3.4	2.2	1.8		28.6	24	23
2	2.3	6.9	3.1	2.0	2.67	1.83		30.6	21	24
3	2.5	6.0	3.9	2.9	2.6	2.1		29.5	27	25
CO_2 p.p.M										
Series 1	102	157	142	3	2.6	4.2				
2	86	103	94	5.2	3.5	4.6				
3	22	2.2	T	T	2.8	2.1				

Table No. 13.

Effects of Carbon Dioxid on the Growth of Barley in Various Solutions

Period of Growth 20 days

Culture and Solution	No of Leaves	Ht. cms.	Length Roots cms.	Green wt. grms.	Dry wt. mgs.	Difference
AP1	2.5	18.2	18			
AP2	3.8	18.6	31			
T1	3	23.0	19	1.72	193	
T2	3	26.2	40	2.6	241	47
Sh1	4	31	20	3.3	330	
Sh2	4	32.2	24.1	3.75	365	35
Cr1	4	26.1	9	2.8	258	
Cr2	4	31.4	14	3.9	340	82
Cr3	3	25	9	2.64		
Cr4	3.2	29.1	12	2.96		

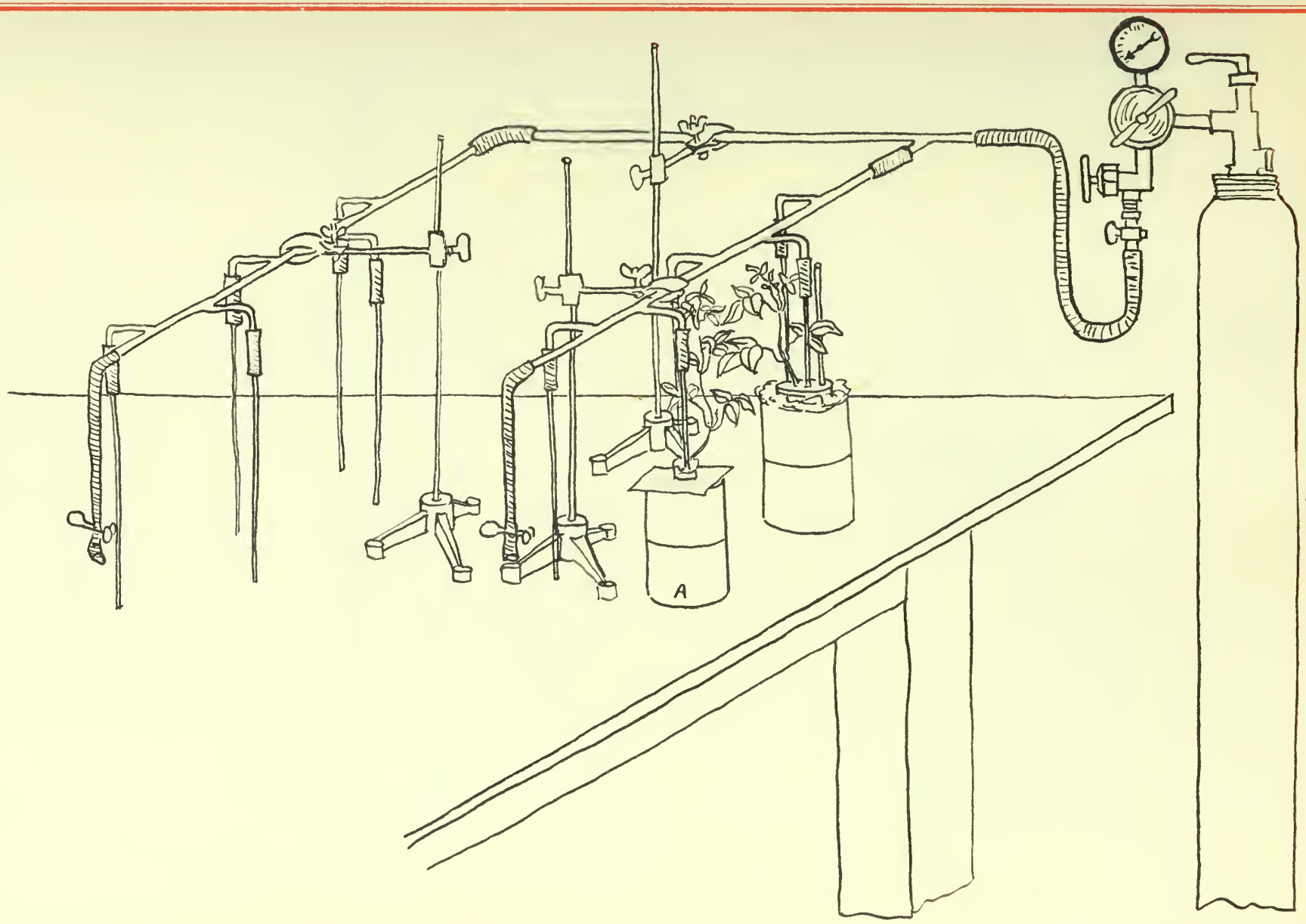

Fig. 1. Distribution apparatus used in minor experiments.

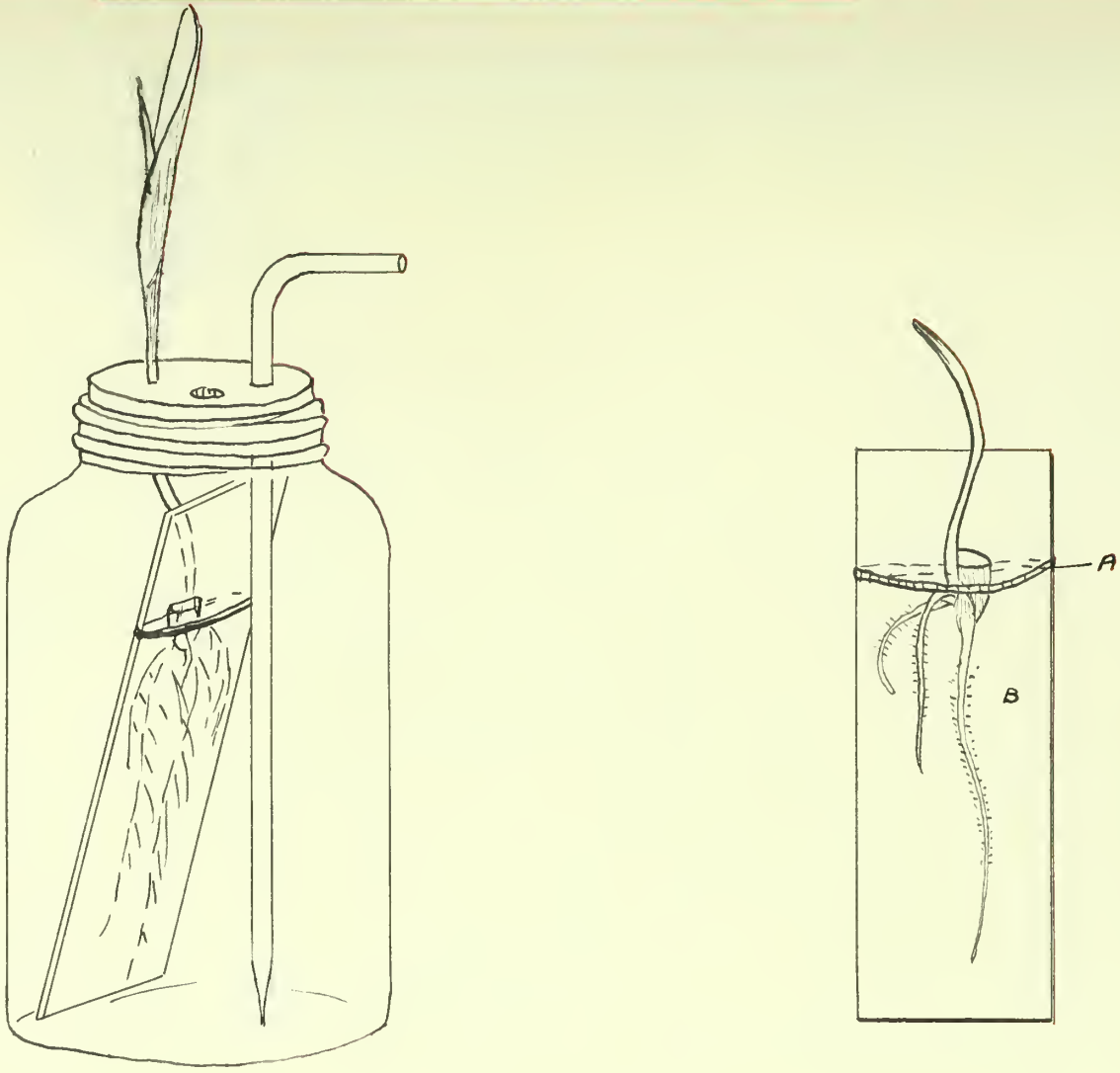

Fig. 2. Method of setting up corn in Experiment I.

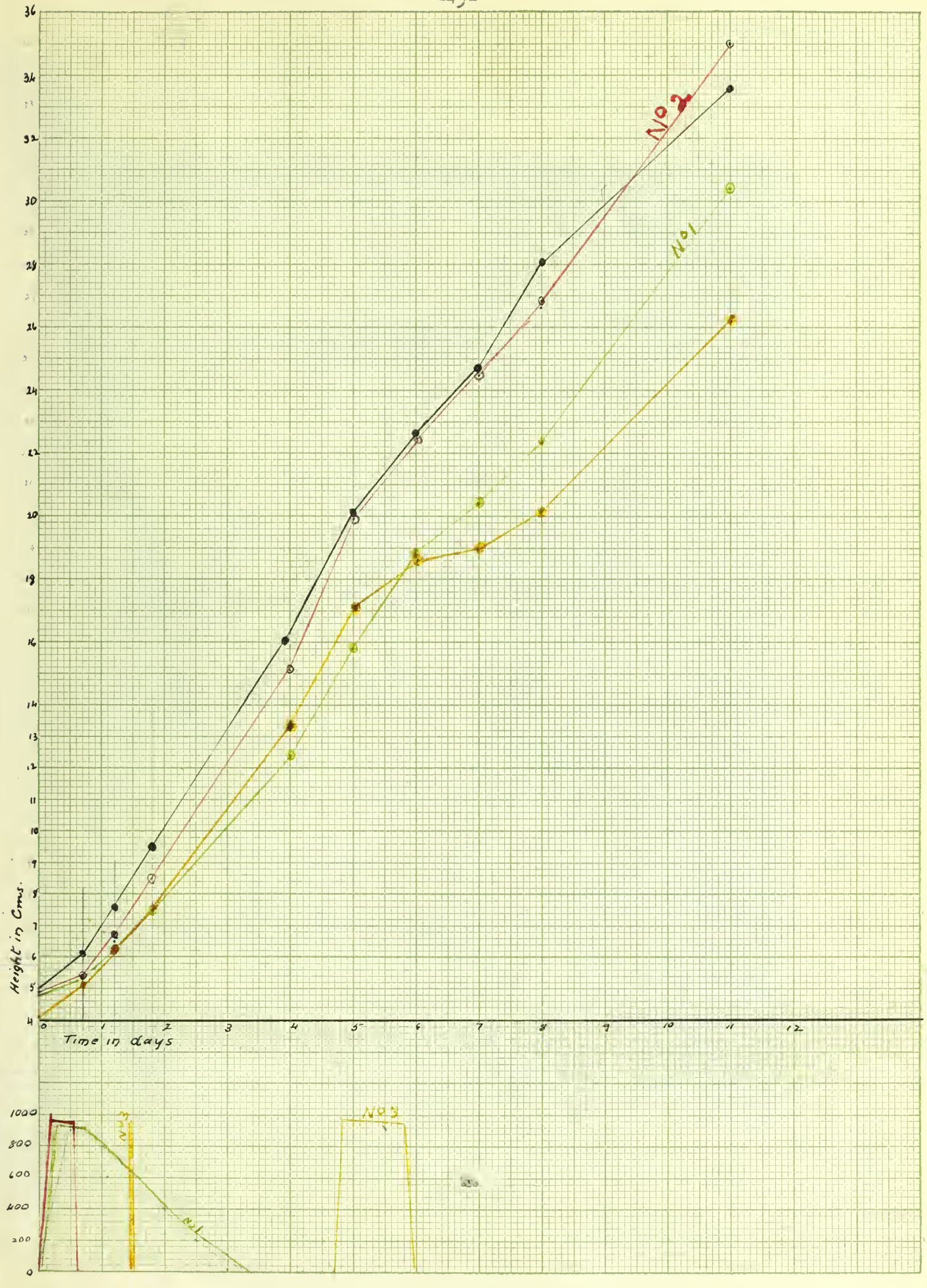

Fig. 3. Effects of carbon dioxid on corn seedlings.

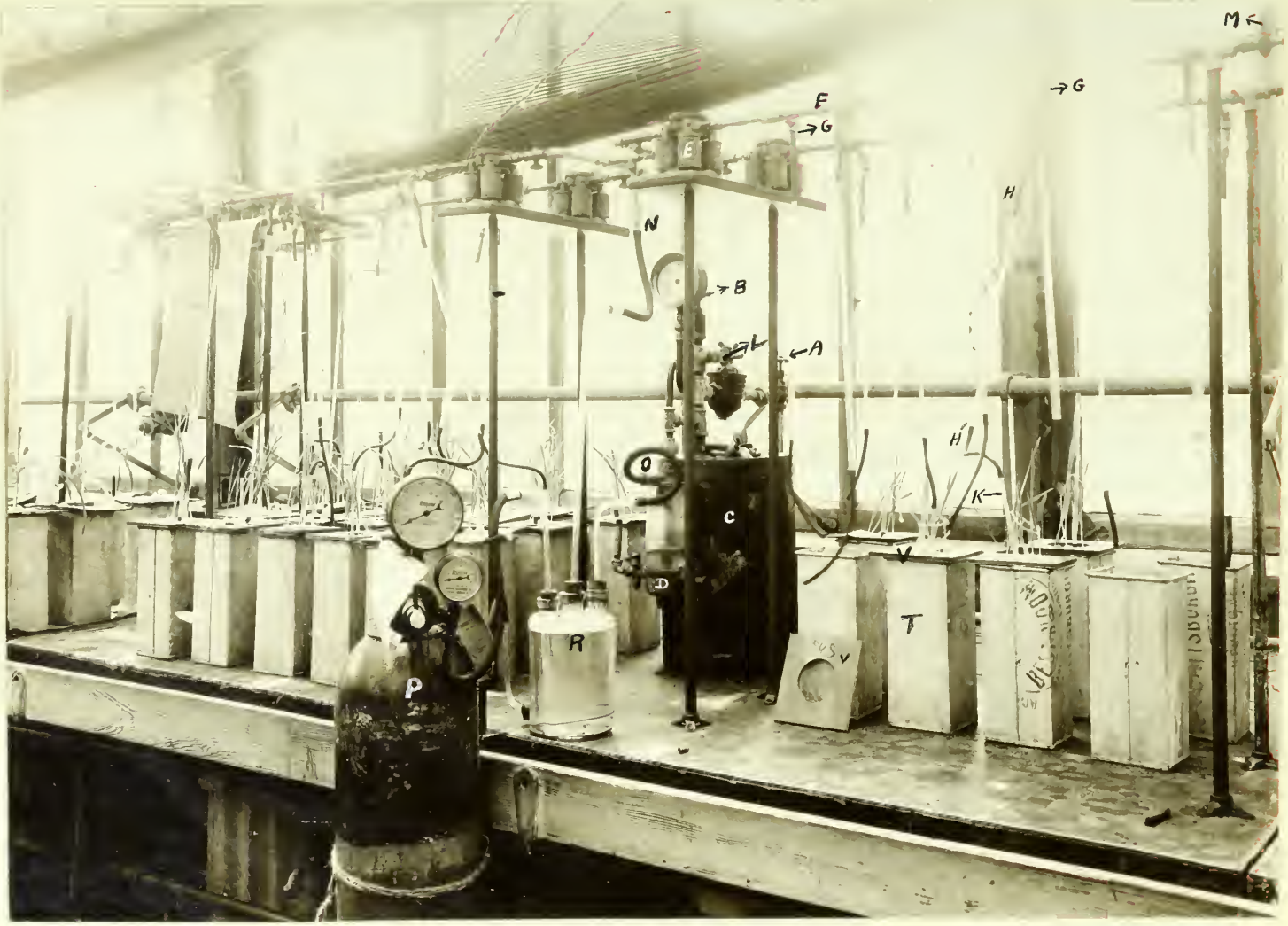

Plate 1. Distribution apparatus as used to test effects of increased partial pressure of oxygen on barley.

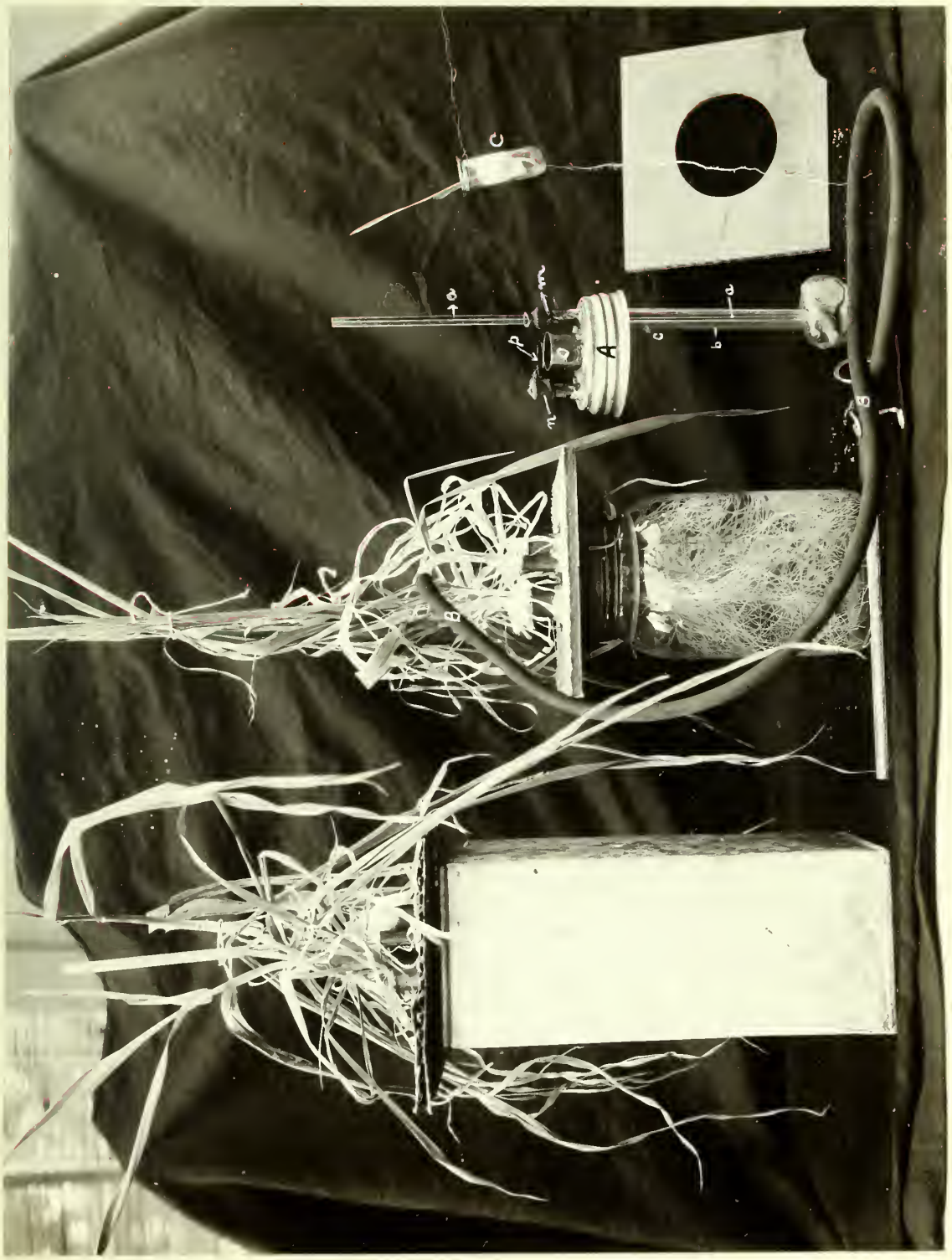

Plate 2. Method of setting up barley.

A

B.

Plate 3. Beans grown to maturity in Shive's solution. Solution not changed.

A. not aerated

B. aerated.

Plate 4. Beans grown in Shive's solution. Solution not changed. Aerated.

Plate 5. Beams grown in Shive's solution. Solution not changed. Not aerated.

Plate 6. Comparison of root systems in Shive's and Crone's solution.

Plate 7. Barley grown on Modified Crone's solution. Two on left continuously aerated. On right not aerated.

Plate 3. Barley grown in Shive's (R_3C_-) solution. Two on left aerated. Two on right not aerated.

Plate 9. Barley grown in Tap water. Two on left aerated. Two on right not aerated.

Plate 10. Barley grown in distilled water. Two on left aerated. Two on right not aerated.

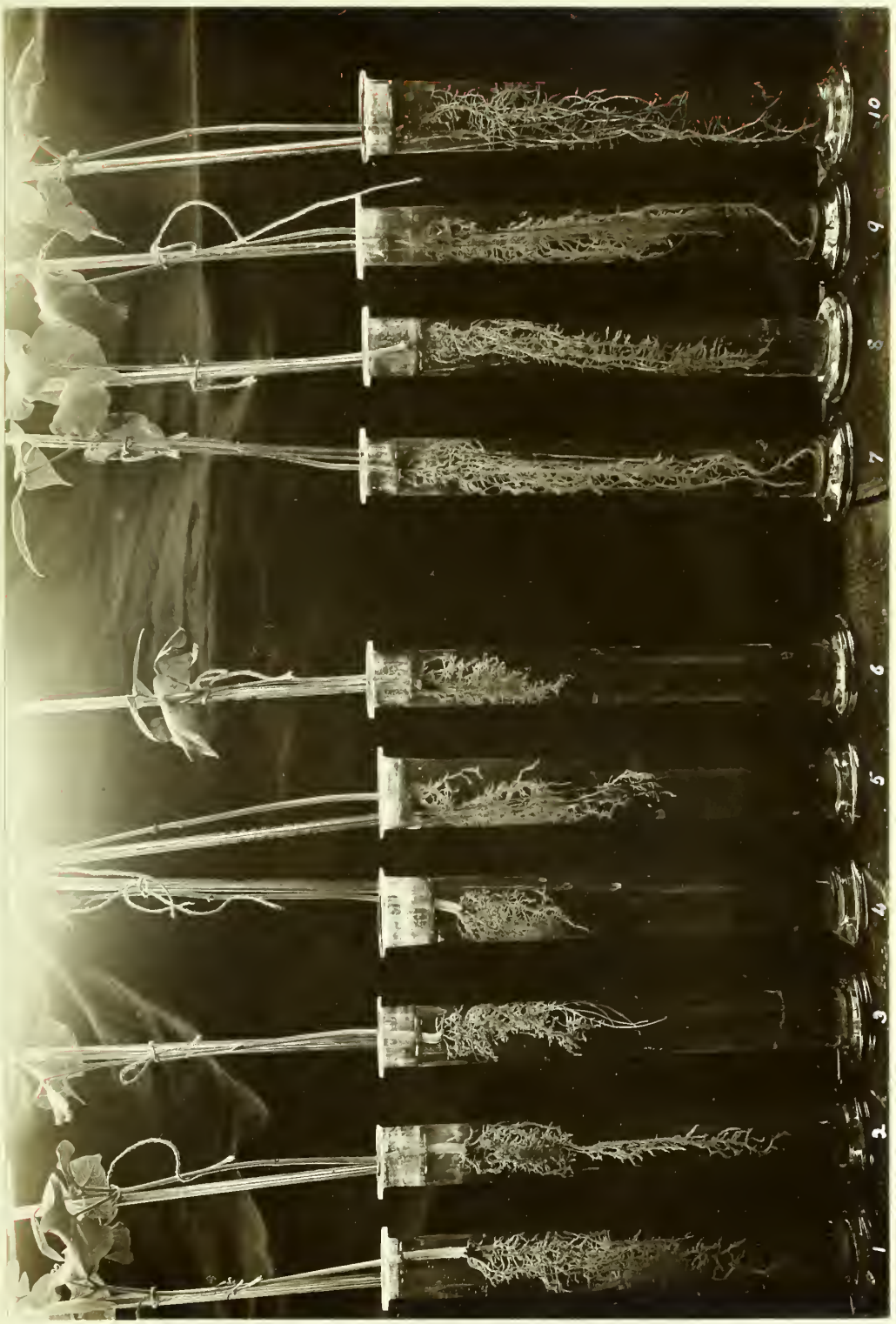

Plate XI. Effect of Oxygen and Aeration on Beans grown in moist sand.
12 aerated once weekly, 3 - 6 oxygen daily; 7 - 10 controls.